

Thermal photon spectra and HBT correlations at full RHIC energy

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Using a model for the evolution of the fireball created in Au-Au collisions at full RHIC energy which reproduces the hadronic single particle spectra and two-particle correlations we calculate thermal photon emission from the hot partonic and hadronic matter. We present predictions for both the emitted photon transverse momentum spectrum and Hanbury-Brown Twiss (HBT) correlations. Surprisingly, we find that due to the strong transverse flow in the model photon emission from hadronic matter is sizeable in the momentum range expected to be dominated by thermal emission and that consequently the HBT radius parameters do not reflect exclusively properties of the partonic evolution phase. We compare to another model calculation where pre-equilibrium photon emission is dominant to illustrate the differences of both approaches.

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I. INTRODUCTION

In the hot and dense system created in a heavy-ion collision, the relevant momentum scales for scattering processes drop as a function of proper time as a large number of particles is created and the system evolves towards equilibrium. Assuming that an expanding thermalized system is created after some initial timescale τ_0 , the relevant momentum scales inside the thermalized matter are then set by the temperature, which in turn drops as the fireball volume expands with time. Thus, by selecting a certain window in momentum for scattering processes, one is preferentially sensitive to a certain proper time window of the evolution. If this window is chosen such that it is below the scales associated with non-equilibrium initial scattering processes, one is, for $\langle p \rangle \approx 3T_i$ with T_i the initial temperature of the system, in principle sensitive to the initial hot and dense phase where hadronic matter presumably undergoes a phase transition to the quark-gluon plasma (QGP) as seen in lattice QCD simulations (see e.g. [1]).

Since electromagnetic probes (such as real photons and dileptons) can escape from the system at all times due to the relative smallness of the electromagnetic coupling constant, a measurement of hard real photon emission can be expected to provide information about the early phases of fireball evolution and ultimately a window to observe the QGP directly [2, 3]. Several such investigations have been carried out for the CERN SPS (see e.g. [4, 5]) In a schematic way this was addressed also in [6] where data measured by the WA98 data [7] could indeed be used to find constraints for the equilibration time. In addition, the measured photon spectrum allowed to distinguish between a boost-invariant longitudinal expansion and a scenario involving initial compression and re-expansion, the latter being favoured by other observables as well [8].

In a recent paper, an approach has been suggested aiming at determining the relevant scales of the spacetime evolution of a fireball created in an Au-Au collision at full RHIC energy [9]. It is the aim of this paper to ex-

plore what amount of thermal photon emission is predicted from the resulting evolution and to what degree a precise measurement of the photon spectrum is able to further constrain the evolution dynamics of the system. In addition to photon transverse momentum spectra, we also discuss predictions for Hanbury-Brown Twiss (HBT) correlation measurements of hard photons and their capability to provide additional information about the early stages of the system.

II. THE MODEL

In this section, we present a model framework for the fireball expansion which in essence is a parametrization inspired by a hydrodynamical evolution of the collision system. This model has been shown to give a good description of both single particle spectra and two particle correlations at RHIC simultaneously for a breakup temperature well below the phase transition temperature. It is described in greater detail in [9], here we only repeat the essential facts:

For the entropy density at a given proper time we make the ansatz

$$s(\tau, \eta_s, r) = NR(r, \tau) \cdot H(\eta_s, \tau) \quad (1)$$

with τ the proper time measured in a frame co-moving with a given volume element, $\eta_s = \frac{1}{2} \ln(\frac{t+z}{t-z})$ the space-time rapidity and $R(r, \tau)$, $H(\eta_s, \tau)$ two functions describing the shape of the distribution and N a normalization factor. We use Woods-Saxon distributions

$$R(r, \tau) = 1 / \left(1 + \exp \left[\frac{r - R_c(\tau)}{d_{ws}} \right] \right) \quad (2)$$

$$H(\eta_s, \tau) = 1 / \left(1 + \exp \left[\frac{\eta_s - H_c(\tau)}{\eta_{ws}} \right] \right).$$

for the shapes. Thus, the ingredients of the model are the skin thickness parameters d_{ws} and η_{ws} and the parametrizations of the expansion of the spatial extensions $R_c(\tau)$, $H_c(\tau)$ as a function of proper time. From the distribution of entropy density, the thermodynamics can

be inferred via the EoS and particle emission is then calculated using the Cooper-Frye formula. For simplicity, we apply the model at the moment only to central and almost central collisions and assume that the flow is built up by a constant acceleration a_\perp , hence $R_c(\tau) = R_c^0 + \frac{a_\perp}{2}\tau^2$ with R_c^0 an initial radial extension as found in overlap calculations. In [9], the model parameters have been adjusted such that the model gives a good description of the data.

III. THE PHOTON EMISSION RATE

The complete calculation of the photon emission rate from a partonic medium to order α_s has been a very involved task [10, 11, 12, 13, 14, 15, 16]. The relevant processes include $q\bar{q}$ annihilation, QCD Compton scattering, bremsstrahlung and $q\bar{q}$ annihilation with subsequent scattering. For the present calculation, we use the parametrization of the rate given in [16].

Vector mesons play an important role for the emission of photons from a hot hadronic gas. The first calculation of such processes has been performed in [17] in the framework of an effective Lagrangian. It has been found that the dominant processes are pion annihilation, $\pi^+\pi^- \rightarrow \rho\gamma$, 'Compton scattering', $\pi^\pm\rho \rightarrow \pi^\pm\gamma$ and ρ decay, $\rho \rightarrow \pi^+\pi^-\gamma$.

Several more refined approaches have been made since then (for an overview, see [18]). In the following, we will use a parametrization of the rate from a hot hadronic gas taken from [19].

A. The photon spectrum

The spectrum of emitted photons can be found by folding the rate with the fireball evolution. In order to account for flow, the energy of a photon emitted with momentum $k^\mu = (k_t, \mathbf{k}_t, 0)$ has to be evaluated in the local rest frame of matter, using $E = k^\mu u_\mu$ with $u_\mu(\eta_s, r, \tau)$ the local flow profile. Following the results in [9] we assume $\eta = \text{const.} \cdot \eta_s$ and $\eta_\perp = \text{const.} \cdot r$ with η_\perp the transverse rapidity in the following. The distribution of entropy density is manifest in the dependence of the temperature $T = T(\eta_s, r, \tau)$ on the spacetime position. In order to account for the breakup of the system once a temperature T_F is reached, a factor $\theta(T - T_F)$ has to be included into the folding integral.

In order to be able to compare with SPS data and our previous model calculations, we present the differential emission spectrum into the midrapidity slice $y = 0$.

IV. PHOTON SPECTRA

The resulting photon spectra are shown in Fig. 1. In (a), we compare the calculation for RHIC with a model calculation for SPS done in the framework outlined above

(essentially this reproduces the results obtained in [6] for SPS in a similar, but slightly less sophisticated framework) and the data obtained for SPS 158 AGeV 10% central Pb-Pb collisions [7].

As expected, the RHIC photon spectrum is characterized by a larger absolute normalization (reflecting a larger four-volume of radiating matter) and a less steep falloff, reflecting a higher temperature of the emission region and/or a larger amount of transverse flow. Roughly, we find a factor two more photons at 2 GeV at RHIC than at SPS.

In order to investigate this ambiguity between flow and temperature in more detail, we compare in (b) and (c) the amount of photon radiation coming from the QGP phase and the hadronic phase, respectively. Surprisingly, while at SPS photon emission from the hadronic phase is a relatively small contribution and the measured photon spectrum directly reflects the initial QGP phase of the evolution and hence the initial temperature, this is not so at RHIC where the QGP and hadronic contributions are found to be equally important.

In order to identify the reasons for this surprising behaviour, we artificially switch off the transverse flow and recalculate the photon spectrum. The result is shown in Fig. 1 (d). This clearly demonstrates that it is the comparatively strong flow in the late hadronic evolution at RHIC (which is in this framework motivated by the strong falloff of the HBT correlations with transverse momentum, see [9]) which leads to the observed importance of hadronic contribution.

An additional factor is the different cooling in the hadronic phase: the system created at SPS conditions is characterized by a large net baryon density at midrapidity. This in turn implies more production of heavy baryonic resonances at the phase transition at SPS as compared to RHIC. Decay processes of these resonances in turn lead to an overpopulation of pion phase space as compared to equilibrium, more so at SPS than at RHIC, which in turn causes more efficient cooling (see [8] and [9] for details). In essence, there is a longer-lasting hadronic phase at RHIC which is hotter on average, leading to more photon emission and increasing the relative contribution from the hadronic phase.

This is, as it stands, rather unfortunate since the slope of the measured photon spectrum is no longer a good measure for the initial temperature at RHIC but rather for the flow in the late phases, which is comparatively well-known from the measured hadronic spectra and HBT correlations already.

V. HBT CORRELATIONS FOR PHOTONS

Using the folding of the rate with the fireball evolution as emission function $S(x, K)$ (describing the amount of photons with momentum K^μ emitted at spacetime point x^μ) we calculate the HBT parameters as [27, 28]

$$R_{\text{side}}^2 = \langle \tilde{y}^2 \rangle \quad R_{\text{out}}^2 = \langle (\tilde{x} - \beta_\perp \tilde{t})^2 \rangle \quad R_{\text{long}} = \langle \tilde{z}^2 \rangle \quad (3)$$

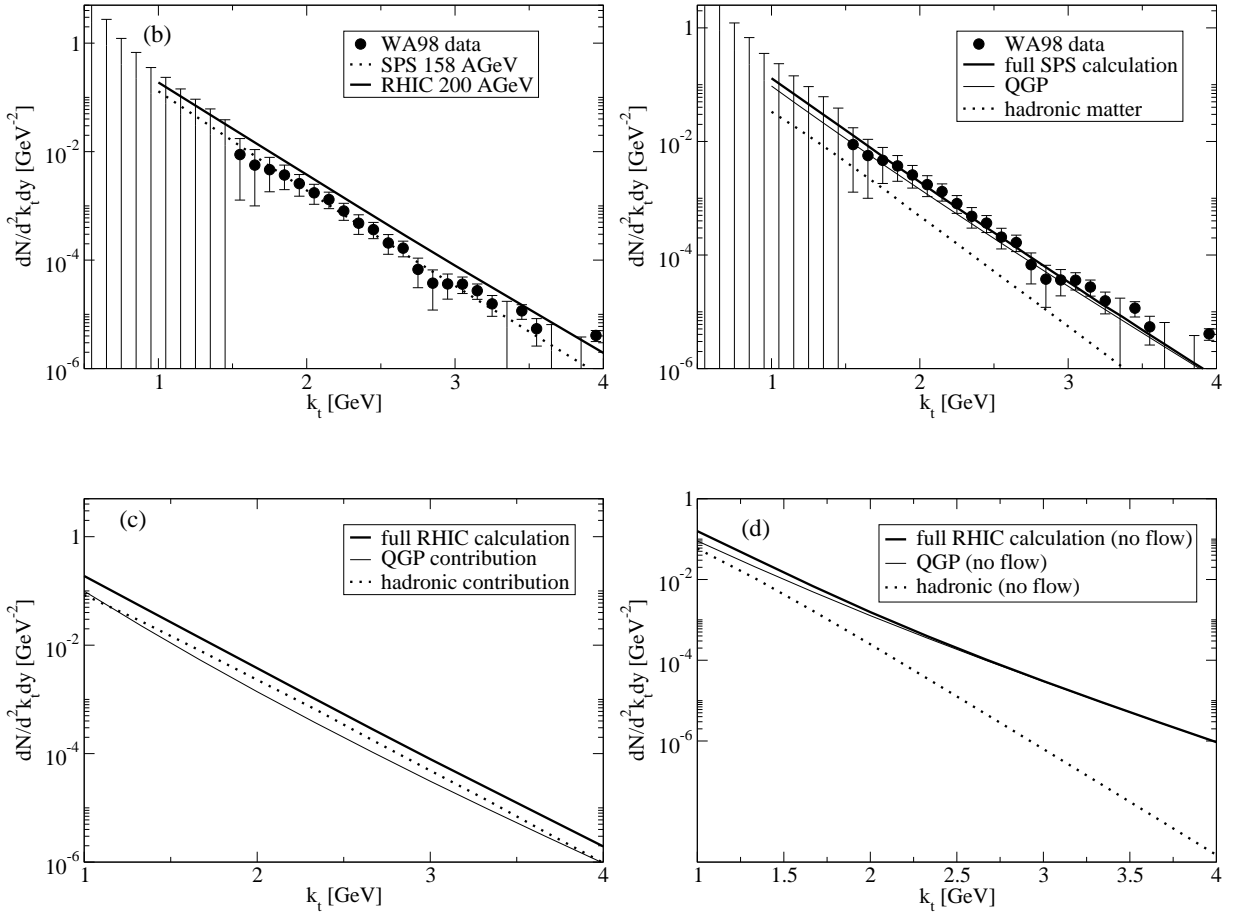


FIG. 1: Upper left: The direct photon spectrum measured at the CERN SPS [7] as compared with the model calculations for SPS (dotted) and RHIC (solid). Upper right: The measured spectrum at SPS, shown with the model calculation for SPS (solid) and the contributions from QGP (thin) and hadron gas (dotted). Lower left: The photon spectrum in the model calculation for RHIC (solid) and the contributions from QGP (thin) and hadron gas (dotted). Lower right: As before, but without taking transverse flow into account when evaluating the photon emission from a given volume element.

with $\tilde{x}_\mu = x_\mu - \langle x_\mu \rangle$ and

$$\langle f(x) \rangle(K) = \frac{\int d^4x f(x) S(x, K)}{\int d^4x S(x, K)} \quad (4)$$

Since photons escape without rescattering from all space-time points, we expect R_{side} to be smaller than in a measurement of hadronic correlations, reflecting the fact that photons from the whole volume enter the emission function at all times (in contrast to hadron emission which takes place from the surface until final breakup), and we expect the difference of R_{out} and R_{side} to be more pronounced, based on the observation that photon emission is not dominated by a small time interval at the final breakup of the fireball but shows a broader distribution (see Fig.2).

In Figs.3, 4 and 5 (left panels) we show the three correlation radii and compare with the hadronic HBT in the measured region [9] (we do not make any calculations for low momentum photons since the emission rates based on perturbative expansions cannot be expected to be valid

in this regime).

These expectations are to some degree confirmed. R_{side} appears to be unexpectedly larger for photons than for pions, but in order to deduce the geometrical size, one has to take into account the effects of flow, and here the less steep falloff of the photon R_{side} as compared to the π^+ measurement (reflecting the fact that a sizeable number of photons is emitted early before transverse flow is built up) seems to extrapolate to a smaller value at $k_t = 0$. There is a pronounced difference between R_{out} and R_{side} as expected before, and R_{long} appears to be approximately the same for photons and pions. This is not a surprise since the question of the transverse emission coordinate and hence the difference between surface and volume emission is irrelevant here.

In order to gain more insight into the underlying physics, we present the photonic correlation parameters as they would appear if one could separate hadronic and QGP emission experimentally (Figs.3, 4 and 5, right panels). Consistently, the hadronic correlation radii show larger absolute normalization and steeper falloff with k_t , both

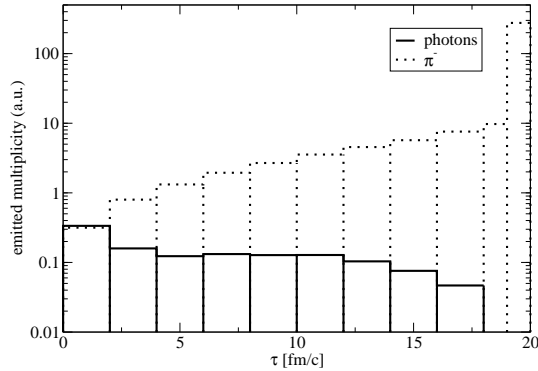


FIG. 2: The emitted multiplicity of photons (solid line) and neg. pions (dotted line) at midrapidity in the momentum regions displayed in Figs. 3, 4 and 5 as a function of proper time τ . Pion emission from the fireball grows roughly with the surface area until finally the hot matter decouples and the remaining pions are freed, therefore the emission is strongly peaked towards late times. In contrast, photon emission takes place from the whole volume at all times and is mainly a function of the average temperature at a given time, hence there is a large contribution from early times.

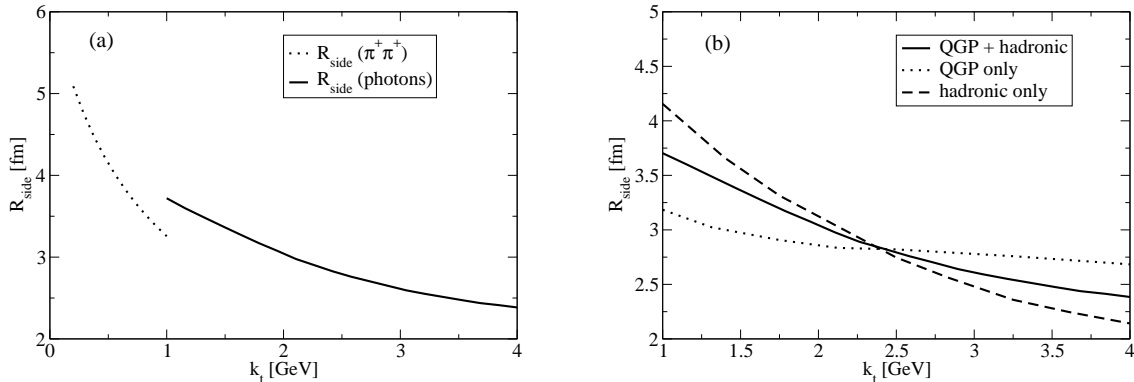


FIG. 3: Left panel: R_{side} as a function of transverse pair momentum k_t for photons (solid) and π^+ (dotted). Right panel: Decomposition of the photonic R_{side} (solid) into correlations among photons emitted from the QGP (dotted) and hadron gas (dashed).

features caused by the flow which at the same time expands the geometrical radius and tends to decrease the size of the observed region of homogeneity with k_t .

In contrast, the early emission of QGP photons shows a comparatively small-sized system characterized by little flow.

Note that R_{side} for the total emission is to a good approximation an average of the individual contributions weighted by their magnitude. However, this does not hold for R_{out} which includes a temporal component as well: The sum of emission durations of hadronic and QGP phase has to be larger than the individual emission durations.

VI. COMPARISON WITH OTHER WORKS

Photon interferometry has been investigated in a number of studies [20, 21, 22, 23, 24]. Here, we focus on a recent study [25] based on the parton cascade VNI/BMS [26] and a subsequent boost-invariant hydrodynamical evolution.

This particular model shows two pronounced differences to the present approach — it contains a pre-equilibrium contribution to the photon yield (not included here) and it is based on a boost-invariant expansion whereas our approach is characterized by accelerated longitudinal expansion.

In order to make a meaningful comparison, we have to correct for the fact that the correlation parameters in

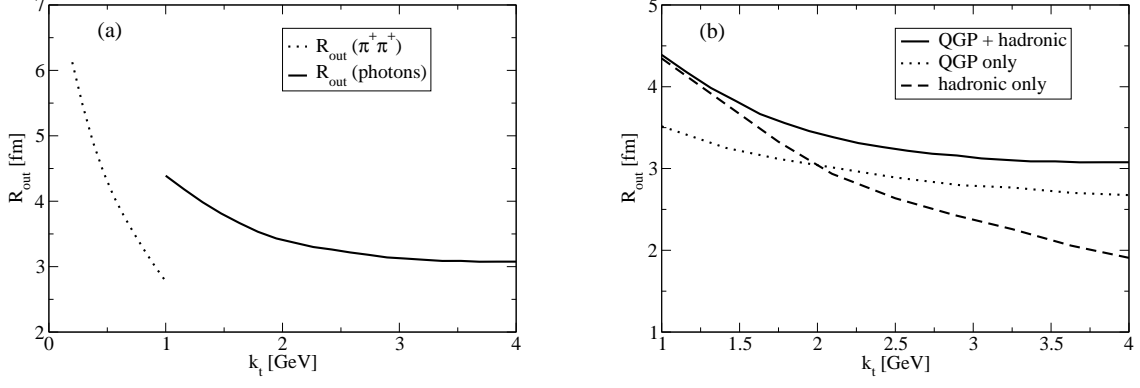


FIG. 4: R_{out} as a function of transverse pair momentum k_t for photons (solid) and π^+ (dotted). Right panel: Decomposition of the photonic R_{out} (solid) into correlations among photons emitted from the QGP (dotted) and hadron gas (dashed).

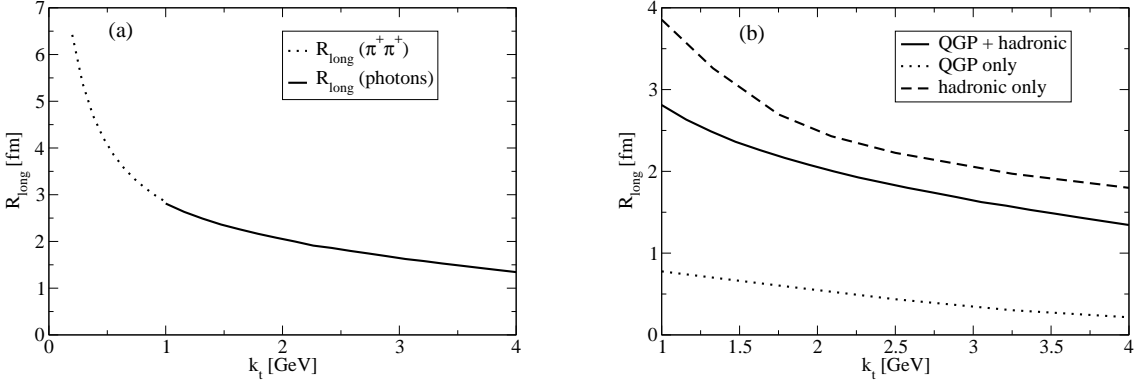


FIG. 5: R_{long} as a function of transverse pair momentum k_t for photons (solid) and π^+ (dotted). Right panel: Decomposition of the photonic R_{long} (solid) into correlations among photons emitted from the QGP (dotted) and hadron gas (dashed).

[25] are calculated for central collisions whereas in our approach we have chosen to calculate for the 30% most central collisions in order to be able to compare with the π^+ HBT results of the model (which describe in turn the measurements). This amounts roughly to a 15% increase of the radii when we go from the values shown in Figs. 3, 4 and 5 to central collisions.

In [25], R_{side} at $k_t = 1$ GeV is found to be 4.6 fm, at $k_t = 2$ GeV 3.8 fm. In our model we find for central collisions similar (though slightly smaller) values of 4.3 fm and 3.5 fm respectively. Thus, R_{side} for photons mainly reflects the initial spatial extension of the emission source and shows little signs of the late source expansion.

The values for R_{out} given in [25] are 4.7 fm for $k_t = 1$ GeV and 3.7 fm for $k_t = 2$ GeV, in contrast to 5.11 fm and 3.9 fm in the present model. Presumably this is a consequence of the different distribution of emission in time: Whereas in [25] the emission at $k_t = 2$ GeV is almost completely dominated by pre-equilibrium contributions

with extremely short duration (leading to $R_{\text{out}} \approx R_{\text{side}}$) this is different in our model, causing $R_{\text{out}} > R_{\text{side}}$.

R_{long} again shows only a moderate difference between the two models: In [25], at $k_t = 2$ GeV a value of 1.6 fm is found as compared to 1.95 fm in the present model. In [25], this is a consequence of the dominance of pre-equilibrium photons in this momentum region which are mainly emitted at times $\tau < 0.3$ fm/c, giving little room for longitudinal expansion, the observed value of R_{long} is then mainly dictated by the uncertainty principle. In contrast, the emission of thermal photons in the present model starts only at 0.6 fm/c when the system has undergone some expansion. Moreover, early longitudinal flow is stronger for a boost-invariant expansion, leading to a further reduction of R_{long} in [25]. Given the fact that we do not include a pre-equilibrium component of photon emission, our value of 2 fm probably overestimates the data somewhat.

The effect of a pre-equilibrium contribution on the HBT

correlations depends on the relative magnitude of the contribution at given transverse momentum. Currently, there is still considerable uncertainty about the absolute magnitude of a pre-equilibrium contribution caused by questions like the role of LPM suppression. According to [29] this may reduce the pre-equilibrium yield by up to a factor 3.5 at 2 GeV transverse momentum. Presumably, a measurement of R_{long} would be most capable of answering the question if a pre-equilibrium contribution constitutes a sizeable fraction of the measured photon spectrum below 3 GeV or not.

VII. SUMMARY

We have presented predictions for the spectrum of thermal photons at full RHIC energy and for two photon correlation radii. This was done in a model which is able to describe both the measured hadronic single-particle spectra and two-particle correlations.

We find that the photon spectrum between transverse momenta $2 \text{ GeV} < k_t < 4 \text{ GeV}$ is not dominated by emission from the hot QGP phase as for SPS conditions [6]. Instead, thermal emission from the hadronic phase turns out to be a significant contribution. This is mainly due to the strong transverse flow at RHIC (which in turn is required for a good description of the hadronic HBT

correlations).

Photon HBT correlations are expected to show a smaller system characterized by less flow than seen in hadronic HBT measurements. This is a consequence of surface versus volume emission processes. However, in the present approach HBT correlations are not exclusively dominated by the QGP phase but reflect an average of the QGP and hadronic evolution phases. Given the importance of thermal photon radiation from the hadronic phase, this is not surprising.

If this scenario turns out to be realized at RHIC then an extraction of QGP properties from photon spectra and correlations may prove difficult. Possibly the cleanest window would then be the high momentum tail dominated by pre-equilibrium physics where the number of emitted photons may still help to understand how frequently scattering processes occur.

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